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Aging Reliability Model for Generation Adequacy

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***Abstract*— As time passes through, components tend to be less reliable because they suffer a degradation produced by aging. Focusing on reliability assessment for generation adequacy, generators reliability model hardly consider this fact. This assumption produces an inaccurate reliability assessment. This paper proposes a novel mathematical formulation that considers aging effect and brings estimation for the degradation of the component. The method is derived from the concept of absorption Markov chain to model component's lifetime. The specific contribution of this work is to present a comprehensive reliability model for generation adequacy.**

***Index Terms*—aging effect, degradation, generation adequacy, Markov chain, reliability assessment.**

I. Introduction

Every component is susceptible to failures and as time passes the tendency of failure increases, until reaching the end of their lifetime in which the component cannot be repaired. For power system reliability evaluation, this fact becomes a complex problem, since there are a high number of components involved with different lifetime. Therefore, there is a need to incorporate a more realistic mathematical model that describes components aging.

For the simplicity, it is common to use a component's reliability model as an alternating renewal process model, with two states: operating and failure [1]. In other studies [2], a multi-state unit model has been proposed. The deficiency on these approaches is the way in which the transition rates are modelled. They follow an exponential distribution, leading to failure and repair rates time independent. The result is a constant availability value. These assumptions underestimate the aging of the component and bring inaccuracies in a realistic reliability of a power system.

Recent investigations focused their attention on the enhancement of power system reliability by introducing distributed energy resources. For instance [3], analyses the influence of a battery energy storage system on generation adequacy in a typical hybrid micro grid environment, showing a reduction in the loss of load probability index and an increment in power system reliability. Reference [4], introduces an analytical method to study the reliability issues on a power system containing wind farms, getting high-reliability standards in power system. A more composite study is given in [5], in which the integration of three renewable energy sources composed of wind, solar and biodiesel energies as well as a storage battery is considered in order to increase the power system reliability. There are studies that justify that distributed generation make a positive impact on power systems reliability when they are accordingly accommodated, nonetheless, these studies are limited since they do not consider components degradation due to aging effects.

On the other hand, aging can be approximated by a transition rate that follows a Weibull distribution [6]. A more accurate approach is presented in [7], in which a component outage model with time-varying aging failure rates employs a staircase function to approximate the aging failure rate curve. Nevertheless, deeper analysis on these studies reveals that these estimations are independent of the component's lifetime and the quantification of its degradation is not clearly given.

This paper presents a mathematical model that deals with the aging effects and brings an assessment for the degradation of the component. The formulation employs the concept of absorption Markov chain to model component's lifetime. In addition, the proposed model is employed for generation adequacy in order to quantify its impact on power systems reliability. The structure of this paper is organised as follows: section II describes the generation adequacy for reliability evaluation; section III presents the proposed reliability model with aging features; in section IV, the theory manifested in previous sections is applied in a case study; section VI shows the aging impact on generation adequacy; finally, section VII brings the conclusion.

II. Generation Adequacy

For reliability studies, the electrical power system is usually divided into three functional zones: generation (HLI), transmission (HLII) and distribution (HLIII) [1]. In HLI, the ability of the total system generation to meet the requirements of total system demand is valued. The ability of transmission and distribution systems to transport energy to points of consumption is not considered. In the adequacy, the generation capacity needed to meet the demand and have reserve capacity to perform maintenance is determined.

There are basic indices in generating system adequacy assessment such as loss of load expectation (LOLE) given in hr/yr, loss of energy expectation (LOEE) given in MWh/yr, Loss of Load Probability (LOLP), and Expected Loss of Load (XLOL) given in MW. These indices can be calculated using quite different approaches, and in this paper, a non-sequential Monte Carlo simulation is employed for the purpose. The method consists in the state determination of each generation unit by sampling, using random numbers uniformly distributed. The sampling is commonly done for a one-hour time slot during a period of study TS (which is commonly a year). If the generated number is less or equal than its unavailability, the unit goes to failure state. The available capacity can then be gotten by combining the hourly operation of all units. Then, for an experiment k, the loss of load duration (LLD_k) is defined as the time in which the generation cannot supply the demand and the energy not supplied due to interruptions of the service (ENS_k), can be obtained by observing the available margin the model given in Fig. 1.

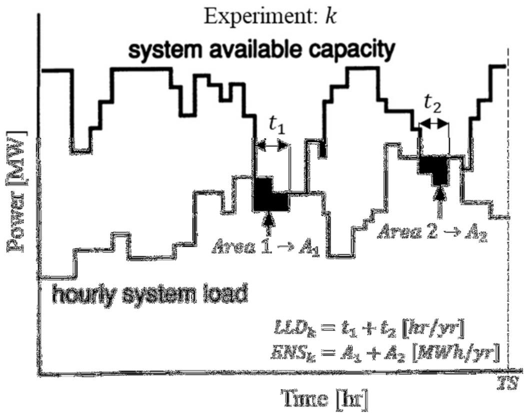

Fig. 1 Generation-demand margin model

These values are saved and one experiment simulation is completed. This process is repeated for M experiments. Finally, the reliability indices can be estimated using the following equations [1]:

$$LOLE = \frac{1}{N}\sum_{k=1}^{M} LLD_k \tag{1}$$

$$LOEE = \frac{1}{N}\sum_{k=1}^{M} ENS_k \tag{2}$$

$$LOLP = \frac{LOLE}{TS}\times 100\% \tag{3}$$

$$XLOL = \frac{LOEE}{LOLE} \tag{4}$$

III. Reliability Model with Aging Features

A. Space State Diagram

The reliability model of some components is not easy to deal with, since sometimes this may involve differential equations. Nevertheless, by applying a Markov chain the modelling becomes simple. Markov chain is a representation of all possible states in a space state diagram connected between them by variables called transition rates. For instance, Fig. 2 shows a transition state of a component with three possible states: 1. operating; 2. repairable failure; 3. obsolescence. The transition from state 1 to 2 is given by λ_r. Nevertheless, in case of repairable failure, the component can be restored and this transition is modelled as a function of the repair rate μ_r. The degradation of the component due to aging is modelled as λ_F.

With this representation the probabilities of being in each state can be estimated as a function of λ_r, λ_F and μ_r.

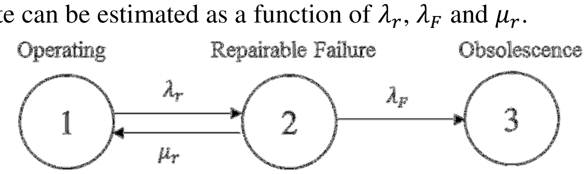

Fig. 2 Space state diagram of component with three states

B. Availability

In mathematical terms, all the states can be represented in a matrix H called stochastic matrix of transition states. This matrix is the infinitesimal generator chain, in which the diagonal terms h_{ii} are the negative of the sum of all states that goes out of the state i.

The terms out of the diagonal h_{ij} are the transition state from i to j state. The probability vector of z possible states is given by [8]:

$$\overline{P(t)} = \sum_{i=1}^{z} C_i \overline{v_i} e^{\upsilon_i t} \tag{5}$$

where υ is the eigenvalues of H^T, $\bar{v}$ is the eigenvectors of H^T and C is a constant given by the initial state; T indicates the transpose of the matrix.

On the other hand, the term availability is typically measured as a factor of reliability and can be calculated as the probability of all states that are in the set of operational states of the component defined in φ. Mathematically is as follows:

$$A(t) = \sum_{i\in\varphi} P_i(t) \tag{6}$$

Applying this criterion for the model given in Fig. 1:

$$H = \begin{pmatrix} -\lambda_r & \lambda_r & 0 \\ \mu_r & -\mu_r-\lambda_F & \lambda_F \\ 0 & 0 & 0 \end{pmatrix} \tag{7}$$

Later, the eigenvalues and eigenvectors of H^T are as follows, respectively:

$$\begin{gathered} a = 2\left(\lambda_r^*\mu_r^* + \lambda_F^*\mu_r^* - \lambda_r^*\lambda_F^*\right) + \left(\lambda_r^*\right)^2 + \left(\lambda_F^*\right)^2 + \left(\mu_r^*\right)^2; \\ \upsilon_1 = 0;\ \upsilon_2 = \frac{-\lambda_r^* - \lambda_F^* - \mu_r^* - a^{0.5}}{2};\ \upsilon_3 = \frac{a^{0.5} - \lambda_r^* - \lambda_F^* - \mu_r^*}{2} \end{gathered} \tag{8}$$

$$\begin{gathered} \overline{v_1} = \left(0 \quad \frac{\lambda_r^* + \lambda_F^* + \mu_r^* + a^{0.5}}{2\lambda_F^*} - 1 \quad \frac{\lambda_r^* + \lambda_F^* + \mu_r^* - a^{0.5}}{2\lambda_F^*} - 1\right)^T; \\ \overline{v_2} = \left(0 \quad -\frac{\lambda_r^* + \lambda_F^* + \mu_r^* + a^{0.5}}{2\lambda_F^*} \quad -\frac{\lambda_r^* + \lambda_F^* + \mu_r^* - a^{0.5}}{2\lambda_F^*}\right)^T; \\ \overline{v_3} = \begin{pmatrix}1 & 1 & 1\end{pmatrix}^T; \end{gathered} \tag{9}$$

Knowing that at $t = 0$ the component is in operational state ($P_1|_{t=0} = 1;\ P_2|_{t=0} = 0, P_3|_{t=0} = 0$), then (6) can written as:

$$\begin{pmatrix}1 & 0 & 0\end{pmatrix}^T = C_1\overline{v_1}e^{\upsilon_1 t} + C_2\overline{v_2}e^{\upsilon_2 t} + C_3\overline{v_3}e^{\upsilon_3 t} \tag{10}$$

Replacing (8), (9) in (10) and solving for C_1, C_2 and C_3:

$$C_1 = 1;\ C_2 = -C_3;\ C_3 = -\frac{\left(\lambda_r^* + \lambda_F^* + \mu_r^* + a\right)^{0.5}}{2a^{0.5}} \tag{11}$$

The solution of a Markov chain for a repairable component considering the aging effect is:

$$\begin{gathered} P_1(t) = C_1 v_{11} e^{\upsilon_1 t} + C_2 v_{12} e^{\upsilon_2 t} + C_3 v_{13} e^{\upsilon_3 t} \\ P_2(t) = C_1 v_{21} e^{\upsilon_2 t} + C_2 v_{22} e^{\upsilon_2 t} + C_3 v_{23} e^{\upsilon_3 t} \\ P_3(t) = C_1 v_{31} e^{\upsilon_1 t} + C_2 v_{32} e^{\upsilon_1 t} + C_3 v_{33} e^{\upsilon_3 t} \end{gathered} \tag{12}$$

The set of operational states is:

$$\varphi = \{1\} \tag{13}$$

Hence:

$$A(t) = P_1(t) = C_1 v_{11} e^{\upsilon_1 t} + C_2 v_{12} e^{\upsilon_1 t} + C_3 v_{13} e^{\upsilon_1 t} \tag{14}$$

the symbol * is used to represent the conjugate value.

C. Mean Time to Absorption

Some states may be "absorbing" because once you reach them there is no turn back to any other state. For instance, in Fig. 2, the obsolescence is an absorbing state. The average time to reach the absorbing state is defined as the Mean Time to Absorption ($MTTA$) and it represent the component's end lifetime.

The $MTTA$ can be obtained using the following procedure [9]:

1. Calculate the matrix $G = H + I$. The G matrix can be written in canonical form considering that there are u transient states (TR.) and w absorbing states (AB.), as shown in (6).

$$G = \begin{array}{cc} & \begin{array}{cc} \text{TR.} & \text{AB.} \end{array} \\ & \left(\begin{array}{c|c} Q & R \\ \hline 0 & I \end{array}\right) \begin{array}{l} \text{TR.} \\ \text{AB.} \end{array} \end{array} \tag{15}$$

Applying this step with the given model gives:

$$G = \left(\begin{array}{cc|c} 1-\lambda_r & \lambda_r & 0 \\ \mu_r & 1-\mu_r-\lambda_F & \lambda_F \\ \hline 0 & 0 & 1 \end{array}\right) \tag{16}$$

2. Determine the fundamental matrix $N = [I - Q]^{-1}$. The rows of N correspond to the state in which the process started.

$$N = \begin{pmatrix} \dfrac{\lambda_r + \mu_r}{\lambda_r \lambda_F} & \dfrac{1}{\lambda_F} \\ \dfrac{\mu_r}{\lambda_r \lambda_F} & \dfrac{1}{\lambda_F} \end{pmatrix} \tag{17}$$

3. The $MTTA_F$ is given by the sum of the terms in row s (started state) of matrix N. The initial state was defined $s = 1$, then:

$$MTTA_F = \frac{\lambda_r + \lambda_F + \mu_r}{\lambda_r \lambda_F} \tag{18}$$

D. Degradation

A point of interest, is to determine the degradation of the component, which is given by λ_F . Hence, from (18):

$$\lambda_F = \frac{\lambda_r + \mu_r}{MTTA_F \lambda_r - 1} \tag{19}$$

IV. Case Study

The study incorporates the IEEE 24 bus reliability test system [10]. Two scenarios are evaluated: with and without aging effect. To simplify the analysis, the assumptions are: 1. all components initially are operating; 2. generators reliability data is as given in Table I. 3. yearly load profile as shown in Fig. 3.

Table I. Generators Reliability Data

Unit Group	# of units	Unit size [MW]	λ_r [failure/hr]	μ_r [repair/hr]	MTTA$_F$ [yr]
U12	5	12	1/2940	1/60	30
U20	4	20	1/450	1/50	30
U50	6	50	1/1960	1/20	50
U76	4	76	1/1960	1/40	50
U100	3	100	1/1200	1/50	30
U155	4	155	1/960	1/40	25
U197	3	197	1/950	1/50	25
U350	1	350	1/1150	1/100	35
U400	2	400	1/1100	1/150	40

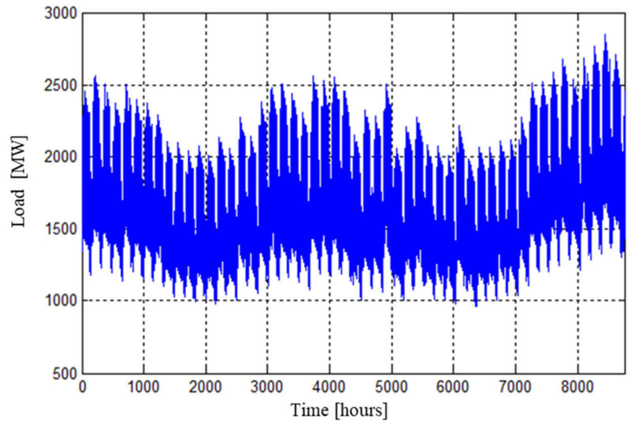

Fig. 3 Yearly load profile

V. Results

A. Case 1: No Aging Effect

The availability behaviour for each generation unit in this scenario is obtained using a renewable basic scheme of states "1" and "2". Recalling, (5), the solution for all generators has the form [8]:

$$P_1(t) = \frac{\mu_r}{\lambda_r + \mu_r} + \frac{\lambda_r}{\lambda_r + \mu_r} e^{-(\lambda_r + \mu_r)t} \tag{20}$$

$$P_2(t) = \frac{\lambda_r}{\lambda_r + \mu_r} - \frac{\lambda_r}{\lambda_r + \mu_r} e^{-(\lambda_r + \mu_r)t} \tag{21}$$

Fig. 4 shows the probability for each generation unit as a function of time t. It reveals that steady state is reached very fast. Hence, the transient part of the solution has a low impact on it.

$P_1(t)$ is the only existing operational state, then the availability takes this function. Knowing this information, a reliability assessment for generation adequacy for a period of 30 years is carried out following the procedure stated in section II. The results are shown in Fig. 6.

B. Case 2: Aging Effect

In this scenario, all generation units follow a space state diagram as given in Fig. 2. The degradation λ_F is unknown, however, it can be obtained using the generator reliability data in (19). The results are shown in Table II.

Table II. Degradation Estimation

Unit Group	λ_F [failure/hr] $\times 10^{-3}$
U12	0.1924
U20	0.0381
U50	0.02270
U76	0.1147
U100	0.0596
U155	0.1147
U197	0.0917
U350	0.0409
U400	0.0239

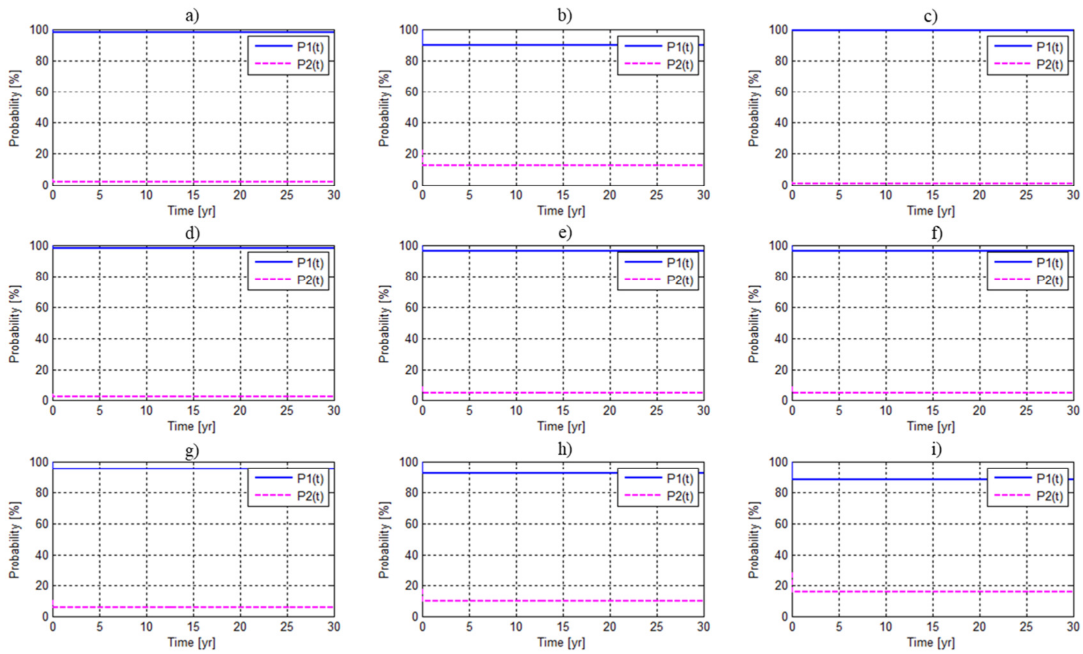

Fig. 4 Probability function consdiering no aging effect: a) U12; b) U20; c) U50; d) U76; e) U100; f) U155; g) U197; h) U350; i) U400

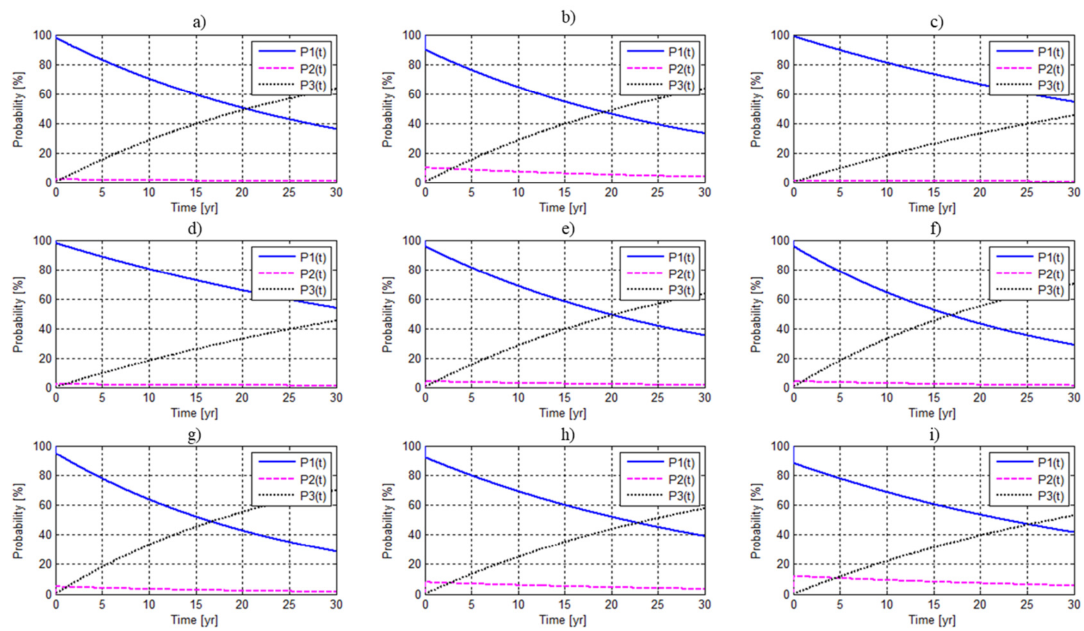

Fig. 5 Probability function considering aging effect: a) U12; b) U20; c) U50; d) U76; e) U100; f) U155; g) U197; h) U350; i) U400

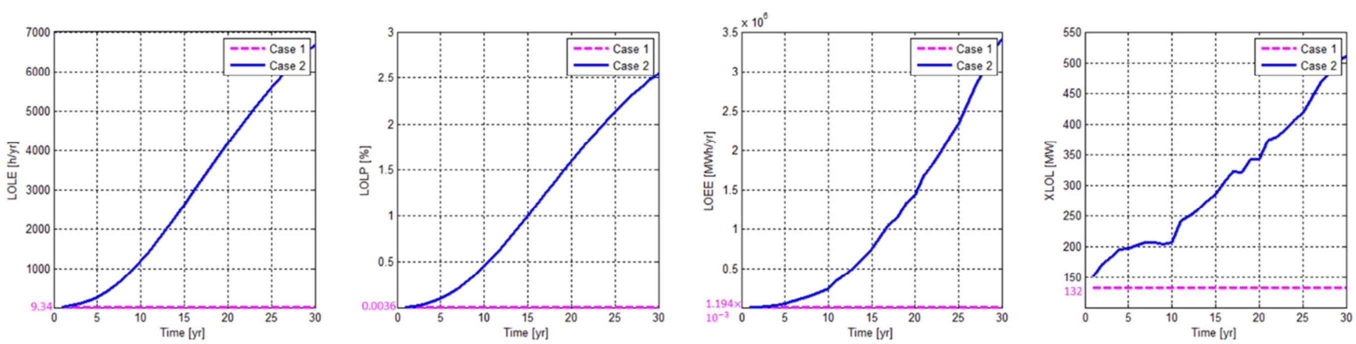

Fig. 6 Reliability indices: a) LOLE; b) LOLP; c) LOEE; d) XLOL

The solution for this scenario is given in (12). As a result the probability for each generation unit as a function of time is obtained as shown in Fig. 5. Same as the last case, availability is presented as $P_1(t)$, since it is the only existing operational state. With this information, a generation adequacy is assessed following the procedure given in section II.

The reliability indices are as shown in Fig. 6. All reliability indices for case 1 takes the same value every year, that is 1194 [hr/yr], 0.0036 %, 1194 [MWh/yr] and 132 [MW] for LOLE, LOLP, LOEE and XLOL, respectively. This is understandable since there is no degradation considered and the reliability for each generation unit is modelled as alternating renewal process between two states. In contrast, for case 2 the reliability indices increases as years pass. The study suggests that the degradation due to aging effect has a strong impact on reliability assessment. In case 2 in Fig. 6, LOLE, LOLP, LOEE and XLOL have the higher values compared with case 1. In year 30 horizon, the maximum values gotten for LOLE, LOLP, LOEE and XLOL are 6684 [hr/yr], 2.55 %, 3.4126×10^6 [MWh/yr] and 510 [MW], respectively.

VI. Conclusion

This paper presents a systematic approach for the quantification of component's degradation due to aging effect as a function of component's lifetime. The mathematical model of the availability is given through the probability function of operational states. This opens a pathway for the use of non-sequential Monte Carlo simulation for generation adequacy assessment.

The results reveal that as time pass, the paper incorporated reliability indices increase considerably, leading to a decrement in power system reliability.

The proposed approach has the potential to describe a more realistic and accurate component's reliability model, which can be extended to HLII and HLIII. Furthermore, the model can be applied to other power system components that entail to a composite system reliability assessment.

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